HIGH-EFFICIENT 60 kW DIESEL GENERATOR WITH CMBE AND INSULATION BASED ON ALUMINIUM NITRIDE

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The design and ventilation system features of a small enclosed diesel generator with combined multi-functional brushless exciter, results of the generator thermal stability analisys as well as the opportunities of design progress application in other capability and enclosure type generators are presented in the paper.

Key words - small-scale power engineering, diesel generator, thermal calculations, severe service conditions, aluminum nitride, combined multifunctional brushless exciter.

I. INTRODUCTION

The development of the distant and under populated north regions, Russian Far East and Siberia has led the creation of low-power diesel generators which are able to work under various emergency and extreme climatic conditions, including fire hazard conditions during repairs of gas and oil pipelines, requiring a highly reliable power supply. It is appropriate to have a generator of a closed design with a combined brushless exciter to work under conditions mentioned above. The cost reduction during building up and the small-scale power industry objects maintenance is the one of the high-priority problems also.

Low and medium power generators ranging from 60 to 600 kW for diesel power stations are being designed at the Electrical Machines Department of the Ural Federal University. The construction was designed on the basis of the Barahchinskiy Electro Mechanical Plant generators of the protected type. A number of changes were made on the prototype construction.

II. EXCITATION SYSTEM

The patent covered combined multifunctional brushless exciter (CMBE) designed at the Electrical Machines Department of the Ural Federal University is proposed as the exciter [1]. The characteristic feature of the CMBE is an unconventional magnetic and electric combination of several electromechanical transducers [2]: two series synchronous exciters with magneto-electrical and combined exciting; asynchronous and inductor subexciters; power source of automatic exciting regulator and rotor current sensor. Physically it is the same as the inversed salient-pole generator: armature with winding which supplies rotating semiconductor rectifier are on the rotor; salient-pole inductor and sub exciting winding are on the stator. Two opposite poles have permanent magnets. There are armature-winding coils of the combined inductor and asynchronous subexciters, adjustable semiconductor supply converter connected with sub exciting winding disposed in magneto-electrical exciting pole-shoes instead of damp winding. Also there are windings of the controlling system power supply and initial exciting as well as rotor current sensor winding disposed on the combined exciting poles.

The experience of design process, manufacturing and maintenance of CMBE applied for diesel and gas-turbine synchronous generator exciting, as well as exciting of hydro generator in small-scale hydroelectric power station with capability from 1 MW to a few tens of MW demonstrated the advantages over the number of worldwide well known brushless exciting systems as follows:

- Complete exciting system independence of the generator voltage, including that of the control channel supply.
- Automating the system completely and ensuring a high level of self-diagnostics
- Guaranteed initial exciting of the exciter (no need in reserve power source, e.g. power batteries, that is very important in emergency conditions operation)
- Ensuring the generator ability to turn on by the self-synchronization method
- Exciting current sensor availability

The new tooth structure and two-row armature winding of the combined sub-exciters were developed and applied to simplify the magnetic system design and to abandon removable poles in the new design of CMBE of the small and medium capability generators. The procedure for calculation of the parameters and inductive subexciter power when using two-row winding was developed.

Reasonable dimensions of the permanent magnets and their shunts were defined to provide the induction value under the combined exciting poles, as well as of the rotor current sensor windings and power source of the automatic exciting regulator without electro-magnetic connection between them.

Increasing of the inductor pole pairs has led to the need of the increasing pole pairs of the armature, and it multiplied the frequency of the inductive subexciter EMF. These two circumstances allowed having required inductive subexciter capacity and to provide sustainable self-exciting process dynamics.

III.Cooling system design features

New insulating materials are recommended to be used in the generator and the excitation system. A composition on the basis of aluminum nitride was selected as the isolation material, also it was decided to "encapsulate" the end windings of the electrical machines with epoxide compound with highly-heat conductive fillers on the basis of aluminum granules and aluminum powder. This decision was proposed after cooperative scientific activity results and collaboration of the Electrical Machines department and Rare metals and nanomaterials department of the Ural Federal University which were the base of these decisions application research. As the result of this collaboration new nanostructured oxinitride materials with high-dielectric characteristics (impregnation compounds) were created. A heat-conduction coefficient of these materials is close to 3-3.5 W/m·K, that is 2 times higher than this of well-known impregnating compounds based on boron nitride. Recommendations for increasing of the oxide-nitride materials using efficiency by end-windings encapsulating were given in this work.

The research has shown that aluminum-nitride materials application and end-winding encapsulating allows to lower winding temperatures of low-middle powered electrical machines up to 10-15 C, raising up reliability and increasing insulation life-time up to 2-2.5 times. Also due to lower winding electrical resistance when operating with lower temperature and therefore lower power losses, overall machine efficiency increases 0.5-0.7%, resulting in cost compensation of the high-priced insulation based on aluminum-nitride during the first year of operation.

Beside the greater heat-conduction coefficient, one of the key advantages of this insulation is its moldability. Compound based on this insulation is fed for winding impregnation under the pressure. The new ultrasonic is applied; herewith the electromagnetic core design remains virtually the same, that considerably reduce the cost of production upgrading.

A disadvantage of the current Russian-made diesel-generators design concerned with operating temperature imbalance of the rotor and stator windings. Generally exciting windings have the highest ones. Due to this fact in the new diesel-generator design, the ventilation axial ducts of inductor core are provided and their most suitable dimensions are defined.

The research of ventilation radial ducts occurrence effect in the excitation end winding by use of numerical approach was also conducted and the most suitable parameters of its configuration were defined to maximize the temperature reduce while leaving the manufacturing process with minimum modifications.

It may be concluded from the research data that ventilation ducts in rotor end winding allow to considerably reduce its overheat (by 108 C if 4 ducts), with that its preferable width equals to 2 mm (Fig. 1). Further width increasing does not give better results. The number of ducts over 4 also does not effect on winding overheat, because further winding volume increasing and therefore its power losses will be meaningful and that is why the number of ducts equal to 4 is assumed as effective for the excitation winding.

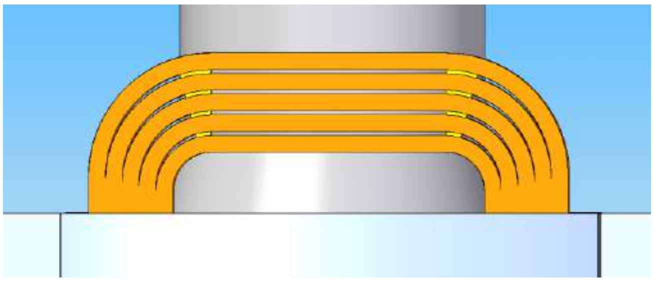

Fig. 1 Rotor winding ventilation ducts

Among the new design solutions of the cooling system there is encapsulating of the stator end windings. For some rotor winding heat unload as well as hydraulic resistance decreasing in the main ventilation passage the stator end winding is placed in so called "capsule" based on epoxide compound with highly heat-conductive fillers. This compound has high heat-conduction coefficient (about 7 W/m·K), and therefore allows to remove the end winding losses directly to the generator housing and to the passing air thus bypassing transitory air layers as well as disposing turbulence sources and parasitic streams over a big number of corners and planes of the end winding coils.

The proposed choice of excitation system, insulation materials and design solutions will enable:

1. Improving the reliability of the diesel power plant
2. Ensuring the complete independence of the generator, including that of the control channel supply
3. Automating the system completely and ensuring a high level of self-diagnostics
4. Reducing operating costs
5. Increasing the life of the generator
6. Changing from protected to totally enclosed type without changing the height of the rotation axis of the device
7. Being able to get implemented for the explosion and fire safety performance

The proposed choice of excitation system, insulation materials and design solutions will enable.

While designing a new generator, retaining, first, the rotation axis height and the prototype's dimensions was set as the main aim. In changing from protected to totally enclosed design, changes in the generator construction are to be minimal in order to maintain the production technology and ensuring the possibility of using the magnetic system of the protected design diesel generators being produced.

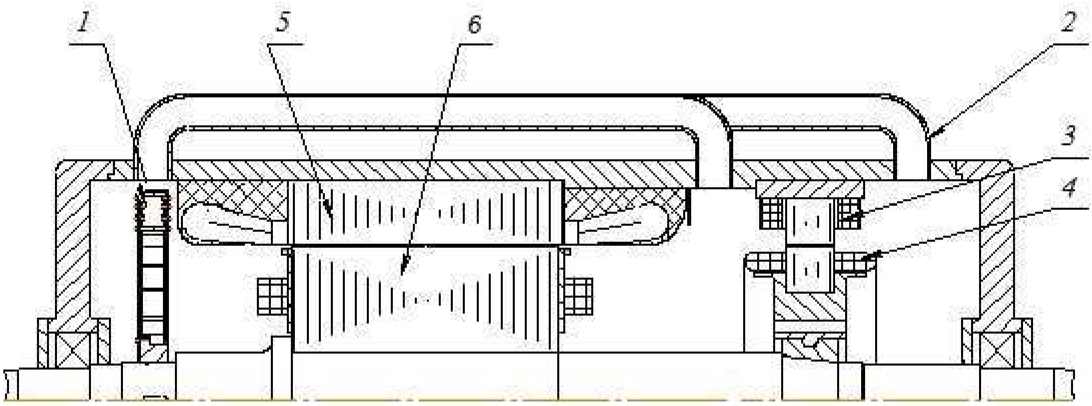

Fig. 2. Structural diagram of the enclosed diesel generator: 1 - centrifugal fan; 2 - cooling pipe; 3 - CMBE inducer; 4 – CMBE armature; 5 - generator stator; 6 - generator inductor

The prototype has the exciter in cantilever located, i.e. outside the casing, which is denied to the enclosed generator. That is why the exciter was introduced into the body of the generator (Fig. 2). Various designs of CMBE generators have been examined. To intensify cooling, a 2-circuit system with the inner contour of the axial type is applied. The internal fan is located on the drive side and the CMBE - at the opposite end shield.

In connection with the changes in the design of the generator it is necessary to develop methods of heat and ventilation calculation

IV. Heat and ventilation calculation in Ansys

A preliminary fan calculation was performed using the method of equivalent hydraulic circuits. Pressure losses of the ventilation paths' sections were calculated, the curve of the centrifugal fan with radial blades was constructed using the technique proposed by A.E. Alekseev [5]. The rated operating condition parameters were determined in the crossing point of the overall characteristic of the ventilation path' pressure losses and the characteristic of the fan pressure. The air flow was 0.098 m^3/s in the internal loop and 0.964 m^3/s in the external one. Peculiarities of the fan calculation are given in [6].

The check calculation of both ventilation circuits was then performed using the final volume method in Ansys CFX. The boundary conditions of the internal circuit were not specified due to the circuit being closed. The discharge was determined by the total mass flow rate in the cross-section of cooling tubes, divided by the air density and was equal to 0.101 m^3/s. A cylinder of a diameter slightly greater than that of the enclosure was taken as the air volume of the external circuit. The boundary conditions of the "opening" type the relative static pressure of which was 0 Pa were specified on the cylinder surfaces. The air flow was determined in the cross-section at the fan enclosure inlet and was 1.01 m^3/s. As a result, the classical analytical calculation error appeared to be the value of 3% as to the internal circuit discharge and 4.5% as to the external one. Fig 3, 4 show the contours of the air absolute velocities' distribution, obtained in CFX.

The operational effectiveness of the ventilation path was evaluated by calculating the thermal state, using the Ansys CFX and its Conjugate Heat Transfer method to account the heat dissipation in solid bodies. The field winding of the generator is characterized by the greatest overheating level exceeding the allowable values for the insulation class H in the diesel generator. Increasing the number of pipes while reducing the number of edges of the casing tend to reduce

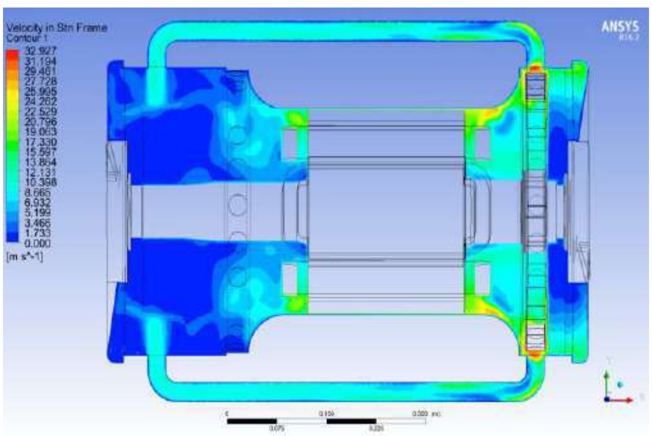

Fig. 3. Inner circuit absolute air velocities' distribution at the axial cut.

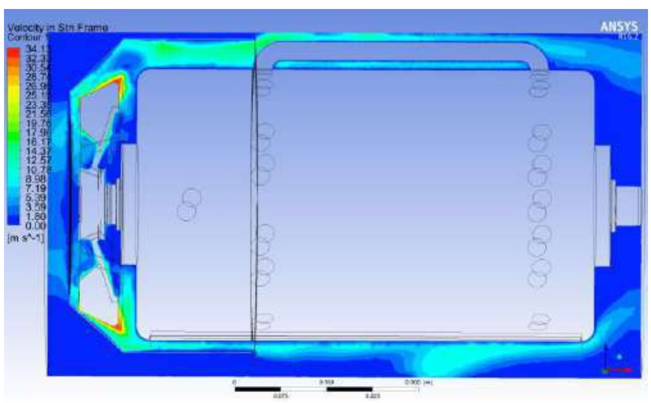

Fig. 4. Outer circuit absolute air velocities' distribution at the cut along the cooling tube.

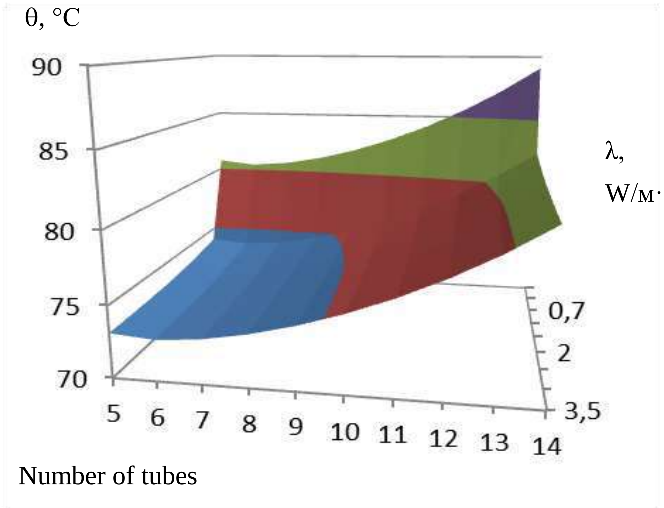

Fig. 5. The dependence of the stator winding overheating upon the number of tubes and the slot insulation thermal conductivity coefficient

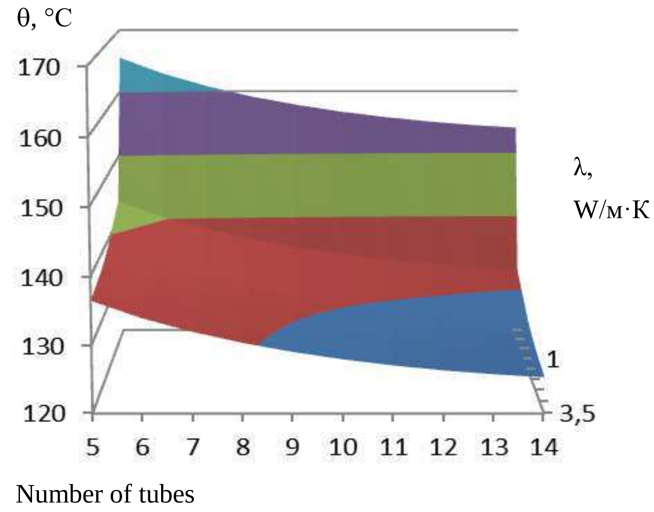

Fig. 6. The dependence of the rotor winding overheating upon the number of tubes and the slot insulation thermal conductivity coefficient.

the imbalance in the excitation windings overheating and reduce overheating of the armature and the field winding to the desired level (Fig 5,6) [7]. The proposed measures reduce overheating of the enclosed generators windings by 15-20%. As a result, diesel generator sets of enclosed design can be made in the sizes of the plants of protected design.

V. CONCLUSION

It is known that enclosed electric machines have mass-scale indices exceeding than those of the corresponding machines of protected construction, which are of the same capacity. However, in developing diesel generators of low and medium power with CMBE, the above mentioned technological solutions were applied which allowed diesel generators with CMBE of the enclosed type to be manufactured in sizes (by the rotation axis height) of diesel generators of the protected design, as well as the protected generators with the same sizes but with much greater efficiency and longer operational life-time. Such decisions should include the use of nanostructured insulating and impregnating materials, based on the use of heat-conducting fillers, which manifests a new approach to windings manufacturing technology both of the generator and brushless exciter, based on the encapsulation of the front and grooving parts, as well as speeding up the internal and external ventilation.

Taken together, these factors allowed designing diesel generators with a new excitation system with improved technical and economic parameters that meet requirements imposed.

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